

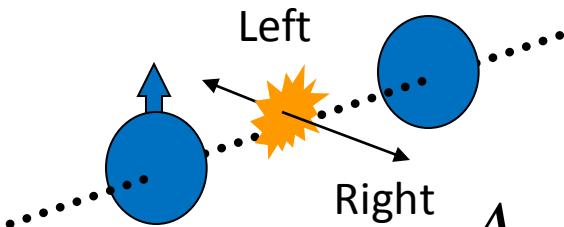
A_N of heavy flavor decay muons in the PHENIX experiment at RHIC

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for the PHENIX Collaboration

- ◆ Introduction
- ◆ PHENIX measurements and results
- ◆ Opportunities in future

Sponsored by DOE, Office of Science

A brief history...



$$A_N = \frac{1}{P} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Theory Expectation (twist-2):

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

$A_N \sim O(0.1\%)$ Theory

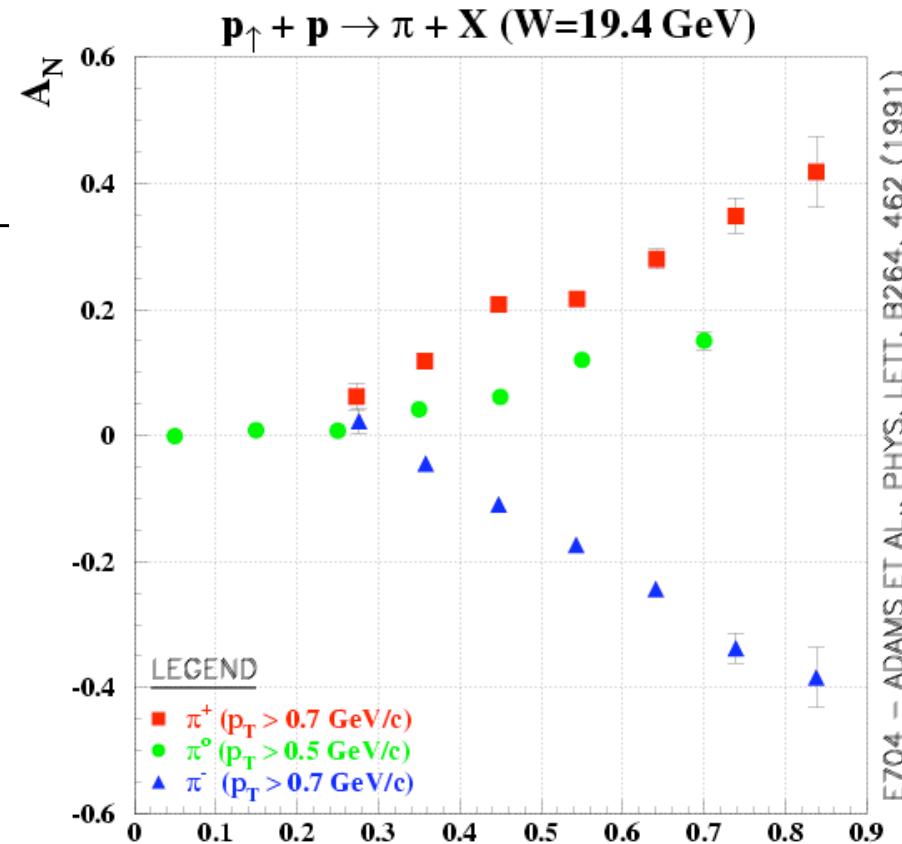
Experiment:

(E704, Fermi National Laboratory, 1991)

$$pp^\uparrow \rightarrow \pi + X$$

 $\sqrt{s} = 20 \text{ GeV}$

$A_N \sim O(10\%)$ Measured



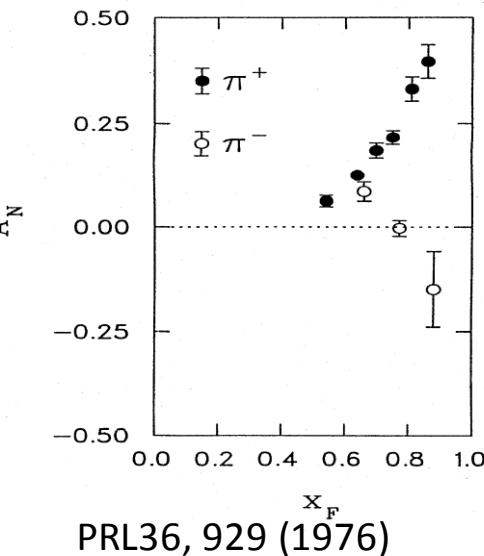
$x_F = \frac{2p_L}{\sqrt{s}}$

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How can we understand them?

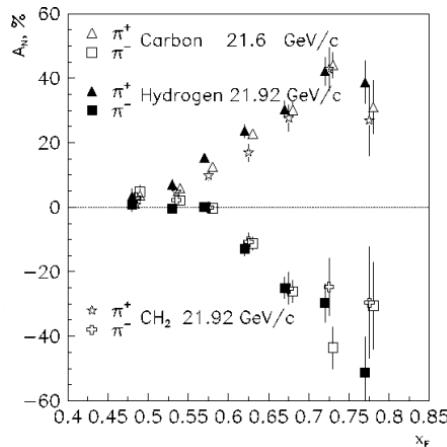
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

ZGS $\sqrt{s} = 5 \text{ GeV}$



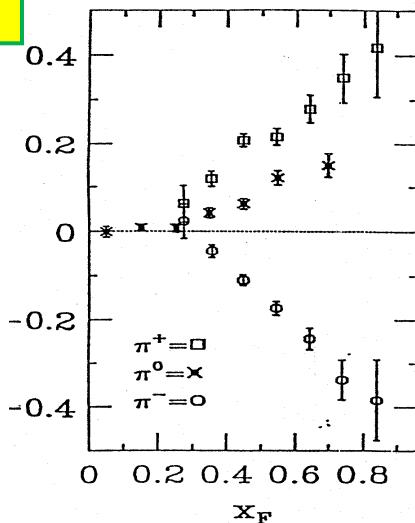
PRL36, 929 (1976)

AGS $\sqrt{s} = 7 \text{ GeV}$



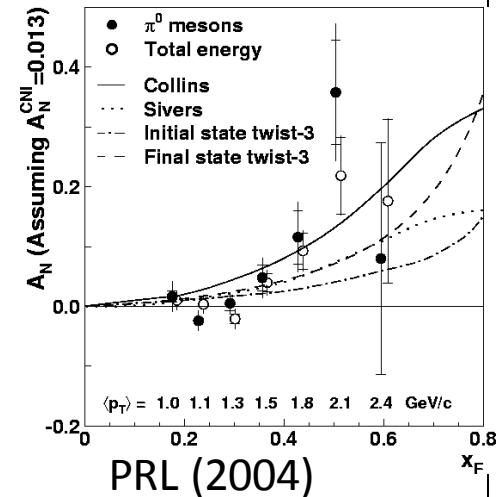
PRD65, 092008 (2002)

FNAL $\sqrt{s} = 20 \text{ GeV}$

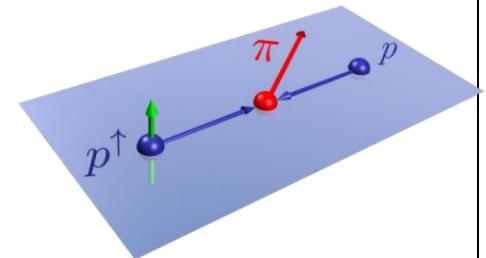


PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC $\sqrt{s} = 200 \text{ GeV}$



PRL (2004)

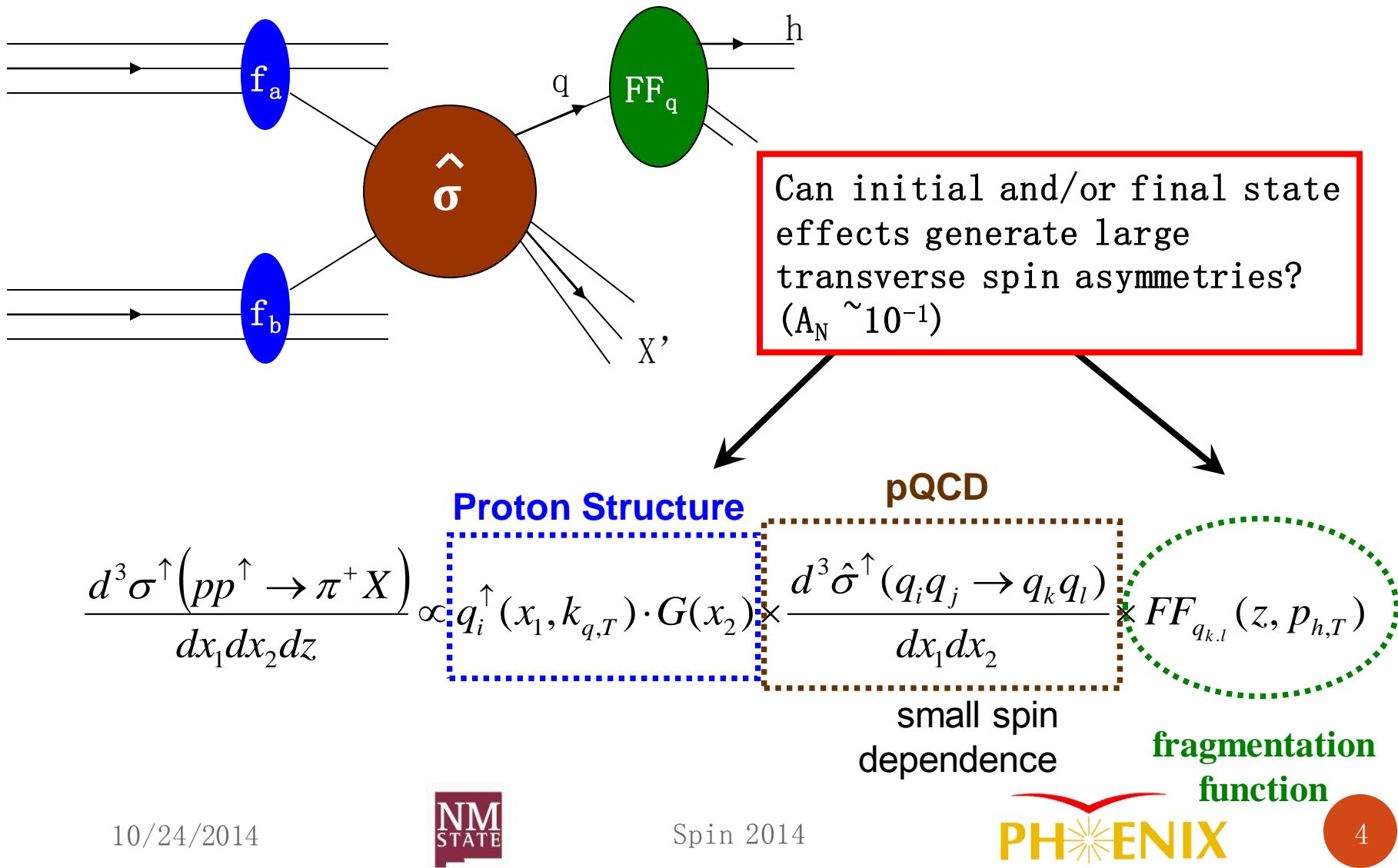


Non-Perturbative cross section

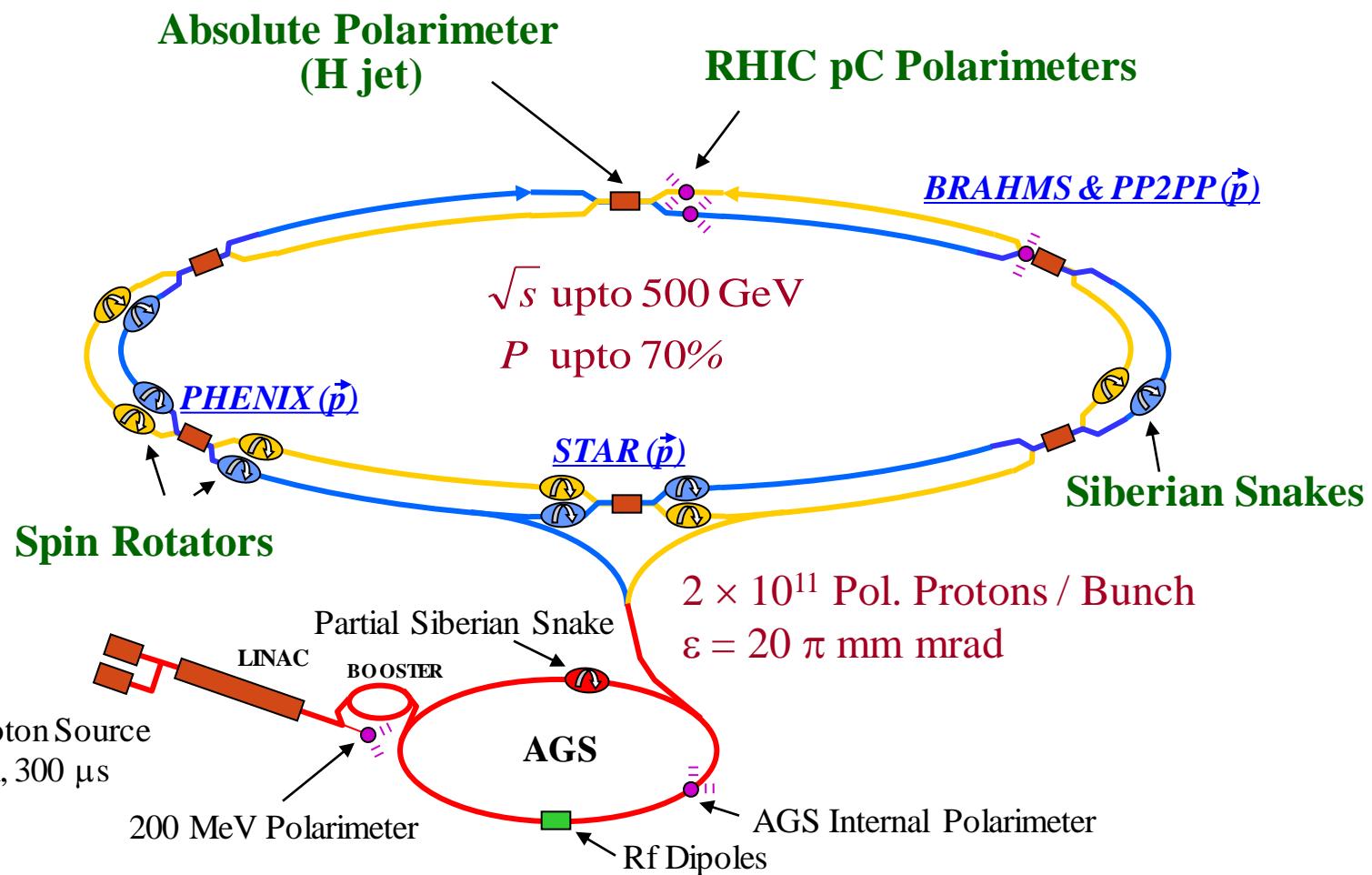


Perturbative cross section

Possible Origin of Large SSAs

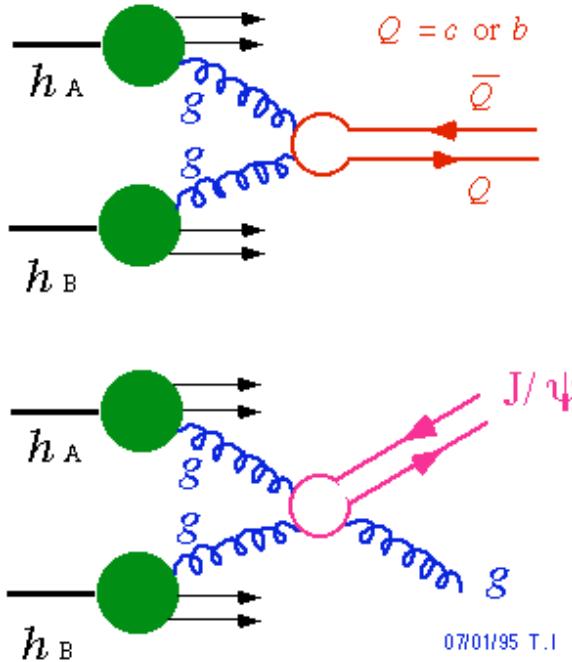


RHIC as Polarized Proton Collider



The gluon contribution on transverse spin

Gluon Fusion



Heavy flavor production is dominated by gluon-gluon fusion at RHIC energy

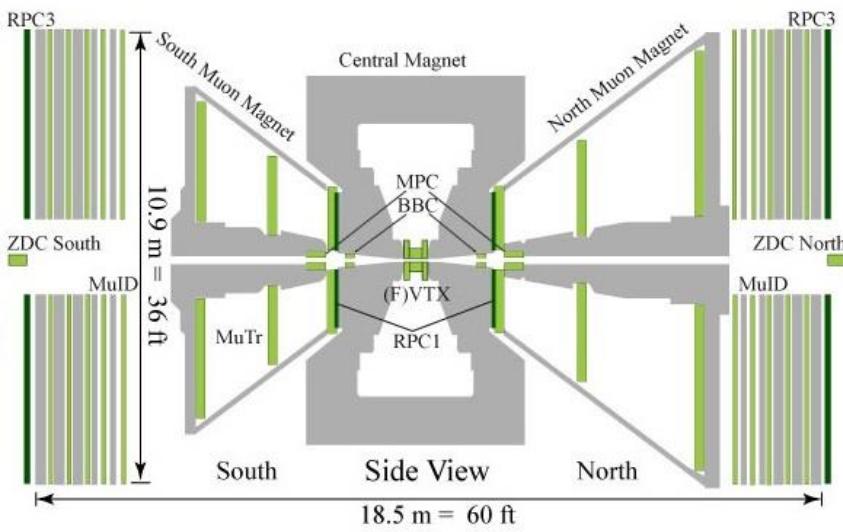
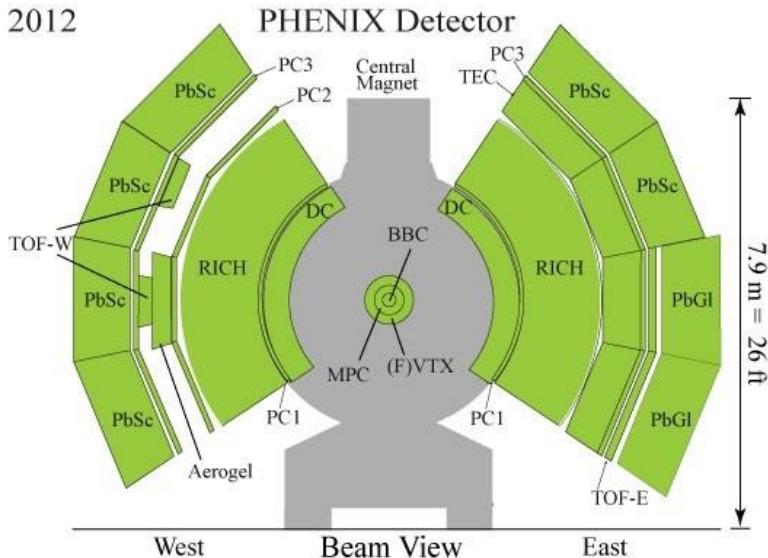
◆ Heavy Flavor production is an ideal tool to investigate the gluon's transverse spin contribution because the gluon has no transversity.

◆ SSA in heavy flavor production revealed the tri-gluon correlations by using the twist-3 collinear factorization framework.

- Z. Kang, J. Qiu, W. Vogelsang, F. Yuan, PRD78:114013 (2008)
- Y. Koike, S. Yoshida PRD84:014026 (2011)

PHENIX Detectors

2012



◆ Central Arm $|\eta|<0.35, \Delta\phi=2 \times \pi/2$

- Drift Chamber (DC)
- PbG1 and PbSc (EMCal)
- Ring Imaging Cherenkov Detector (RICH)
- Pad Chambers (PC)
- Time Expansion Chamber (TEC)
- Silicon Vertex Detector (VTX)

◆ Muon Arms $1.2<|\eta|<2.4, \Delta\phi=2\pi$

- Muon tracker (MuTr)
- Muon Identifier (MuID)
- RPC (Trig)
- Forward VTX (FVTX)

◆ Muon Piston Cal. (MPC) $3.1<|\eta|<3.9$

- Photons
- MPX-EX upgrade (2015)

◆ Global Detectors (Lumi, Trigger, local Pol.)

- BBC
- ZDC (neutron)

Spin 2014

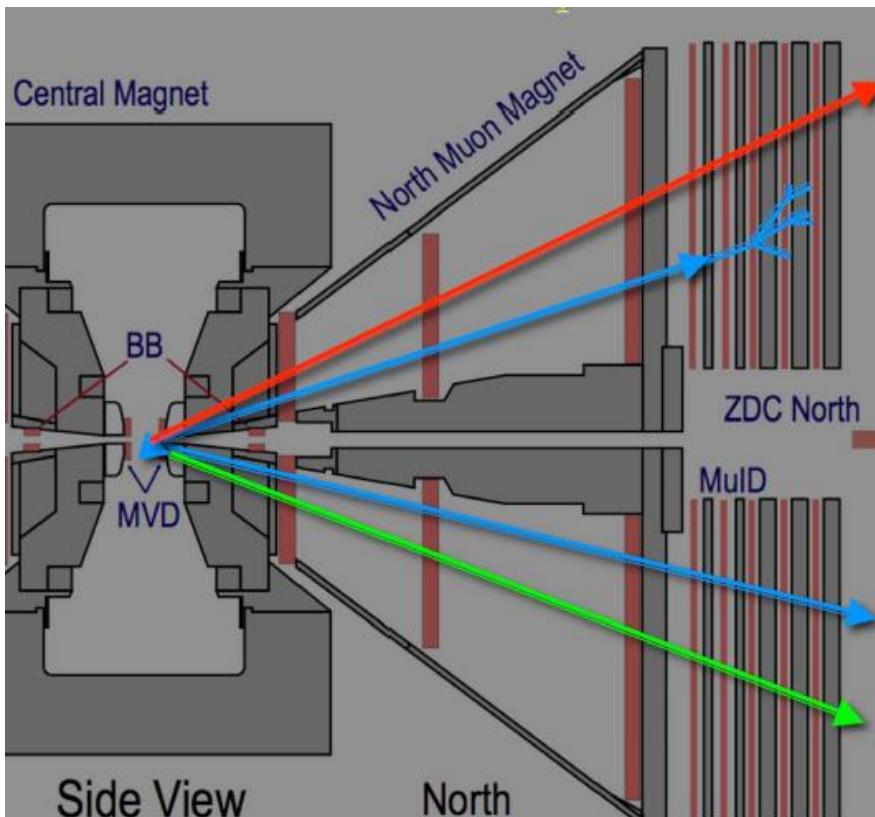
PHENIX

Measurement of Heavy flavor decay muon

Muon Spectrometer:

- $1.2 < |\eta| < 2.4$
- Azimuthal: $\Delta\Phi = 2\pi$

$$A_N^{Phys} = \frac{A_N^{Incl} - r \cdot A_N^{BG}}{1 - r} \quad r = \frac{N^{BG}}{N^{Incl}}$$



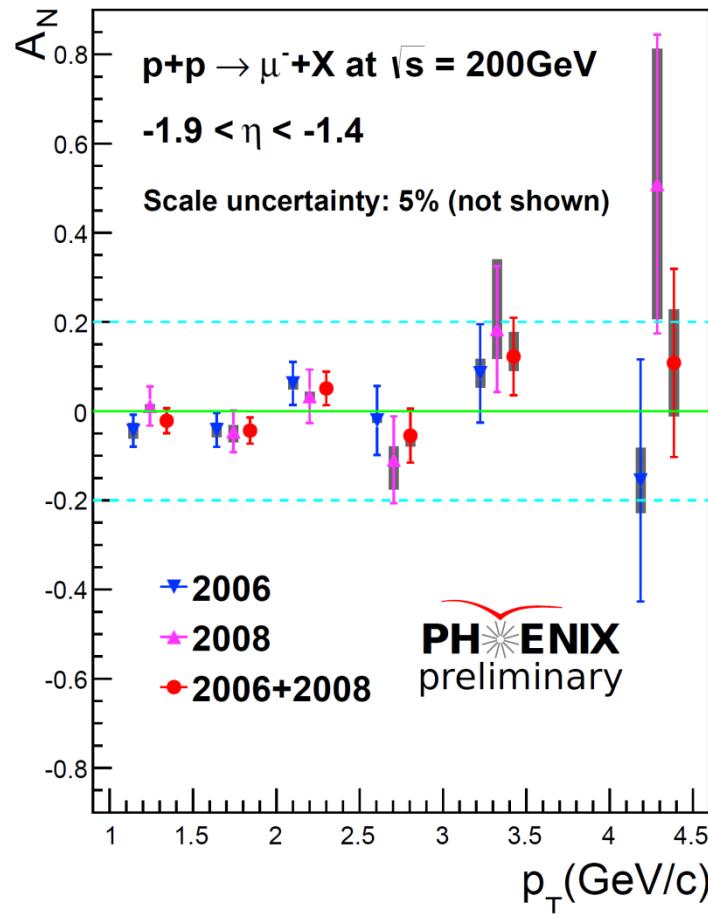
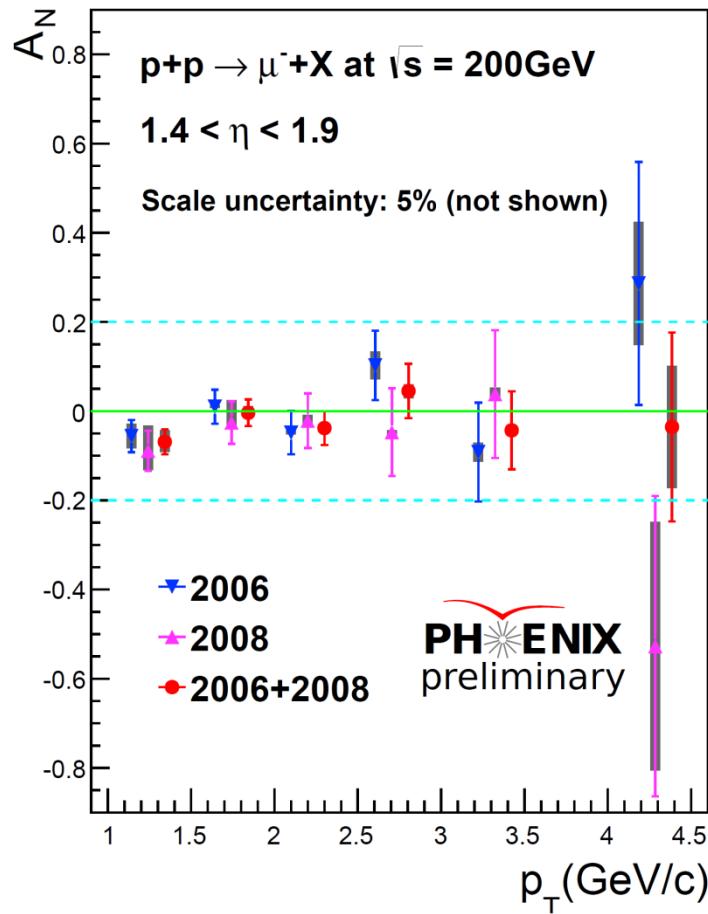
Inclusive Muons

- ◆ Heavy Flavor decay muons
- ◆ Stopped hadrons → Distinguished background
- ◆ Punch-through hadrons
- ◆ Hadron decay muons

Integrated Luminosity and Polarization

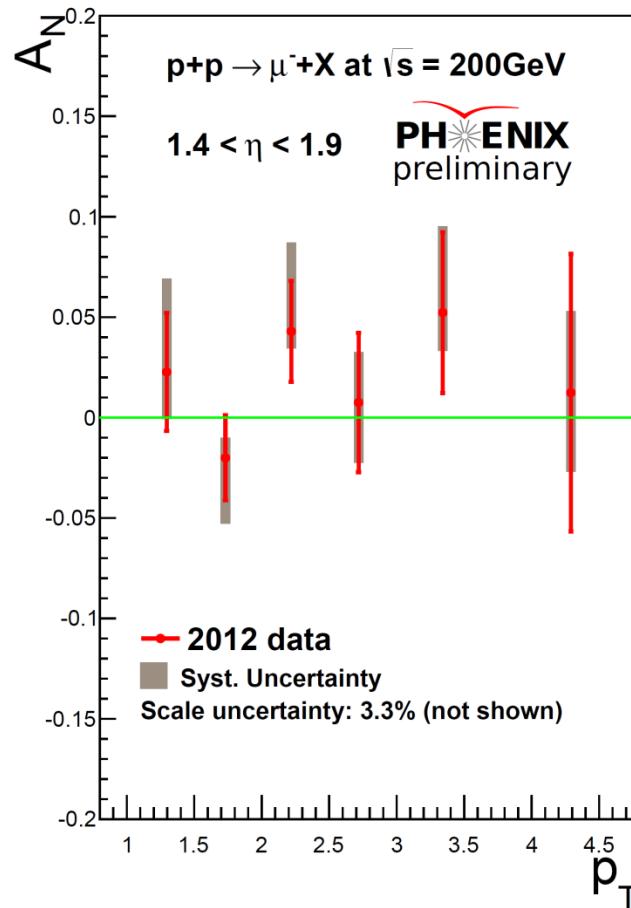
Year of RHIC Run	Energy [GeV]	Polarization [%]	Recorded L [pb⁻¹]	FOM (P²L) [nb⁻¹]
2002	200	15	0.15	3.4
2005	200	47	0.16	35
2006	62.4	48	0.02	4.6
2006	200	50	2.7	700
2008	200	45	5.2	1100
2012	200	60	9.2	3300

Old Result A_N vs p_T

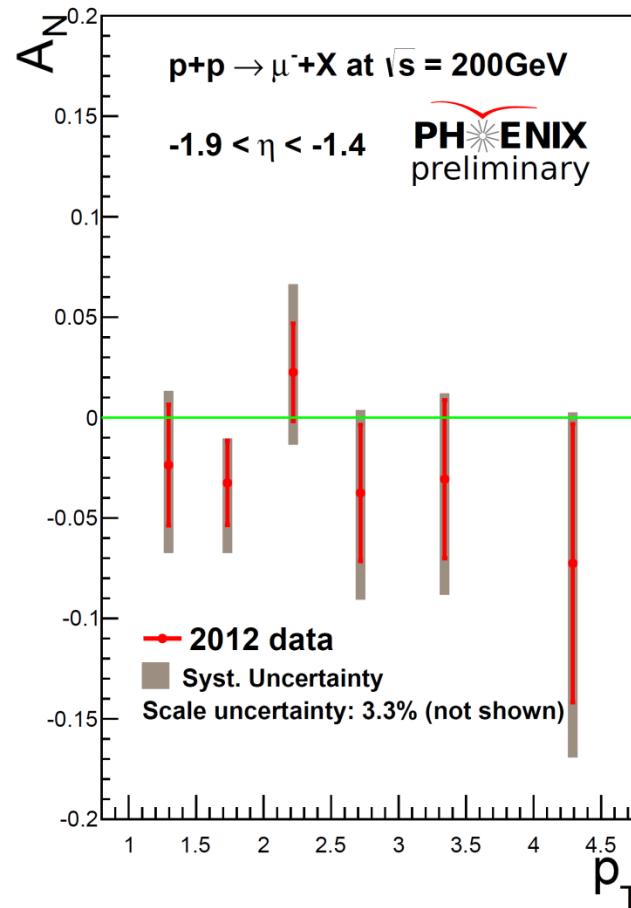


Heavy Flavor A_N VS p_T

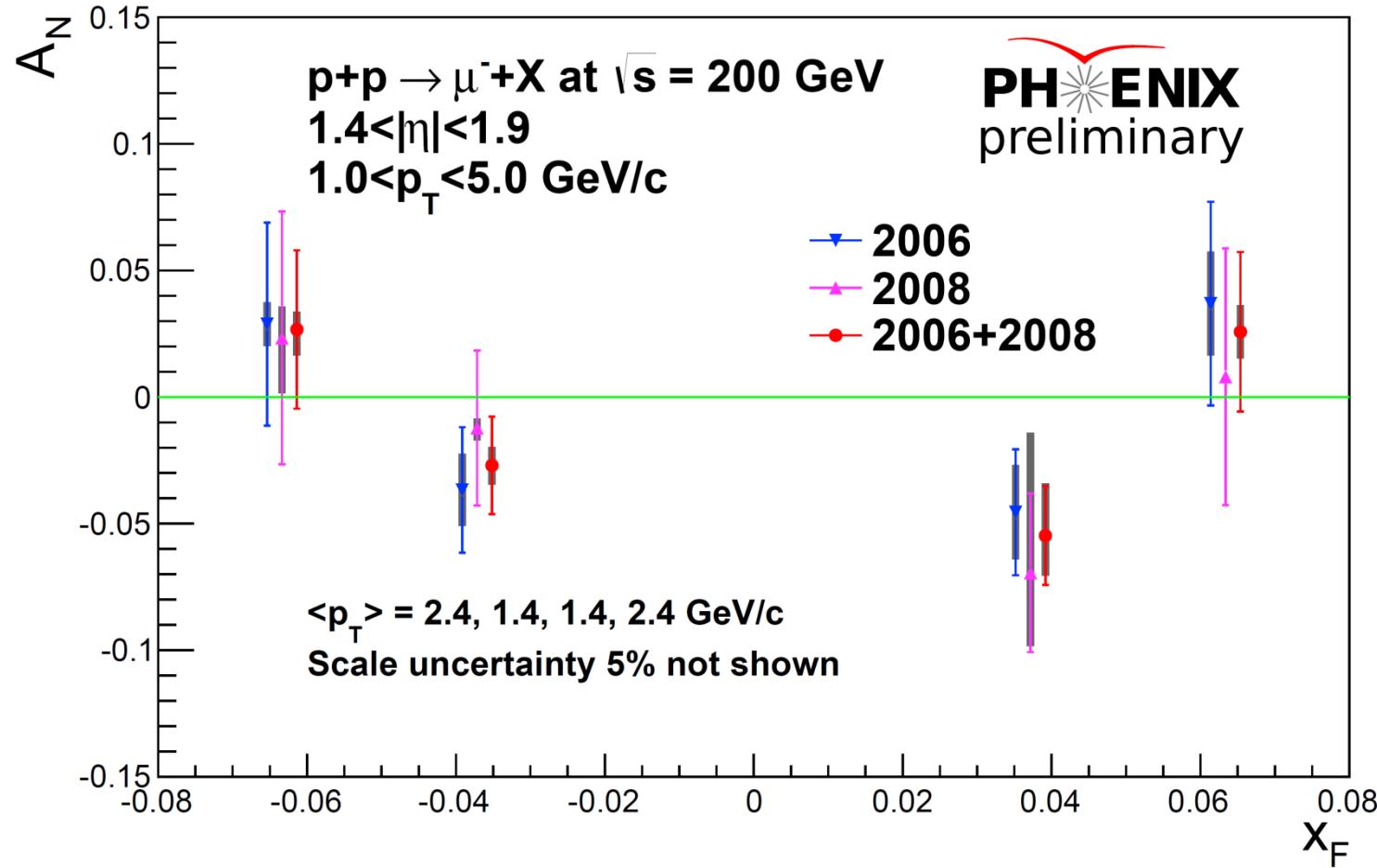
Forward



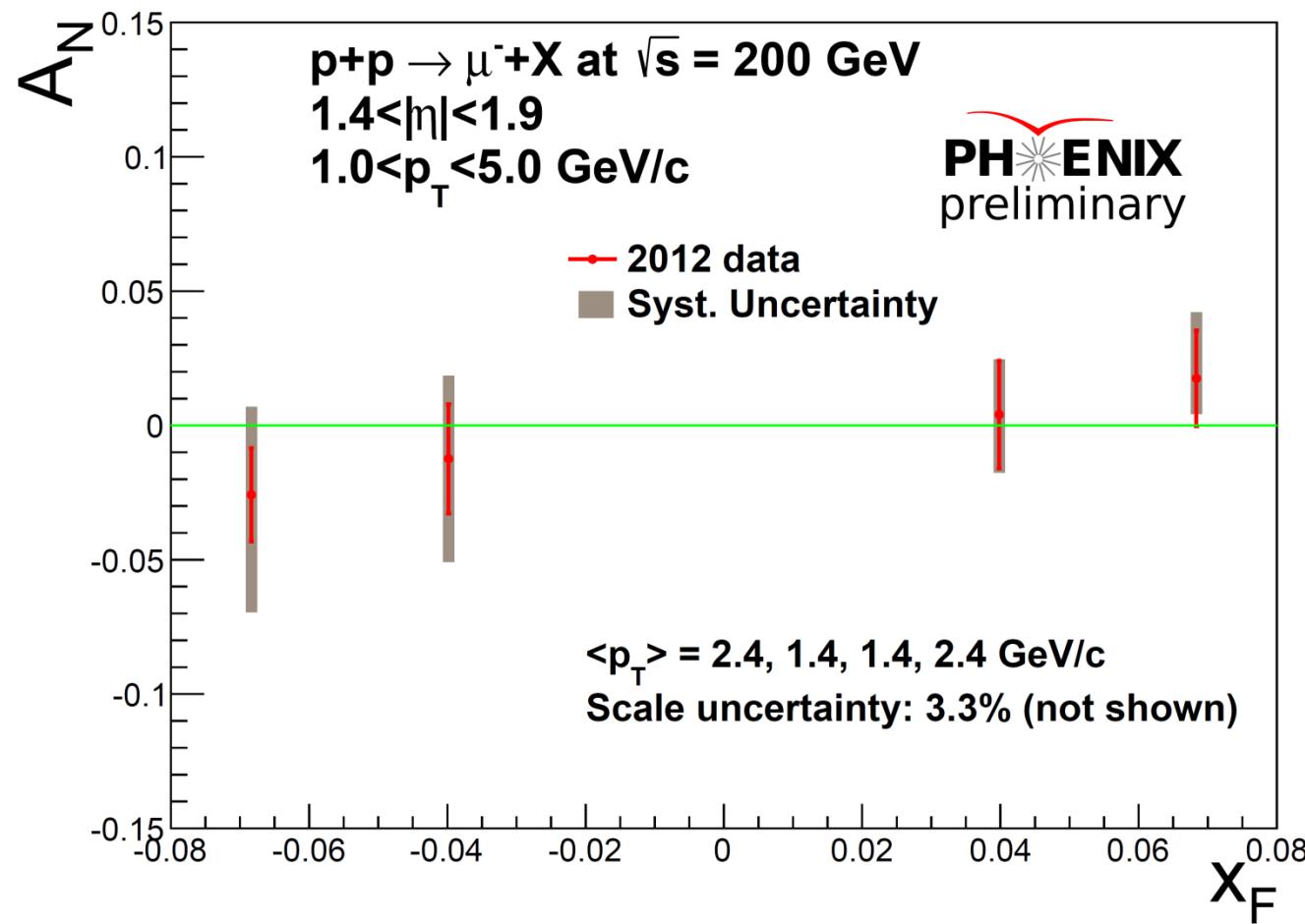
Backward



Old Result A_N vs x_F



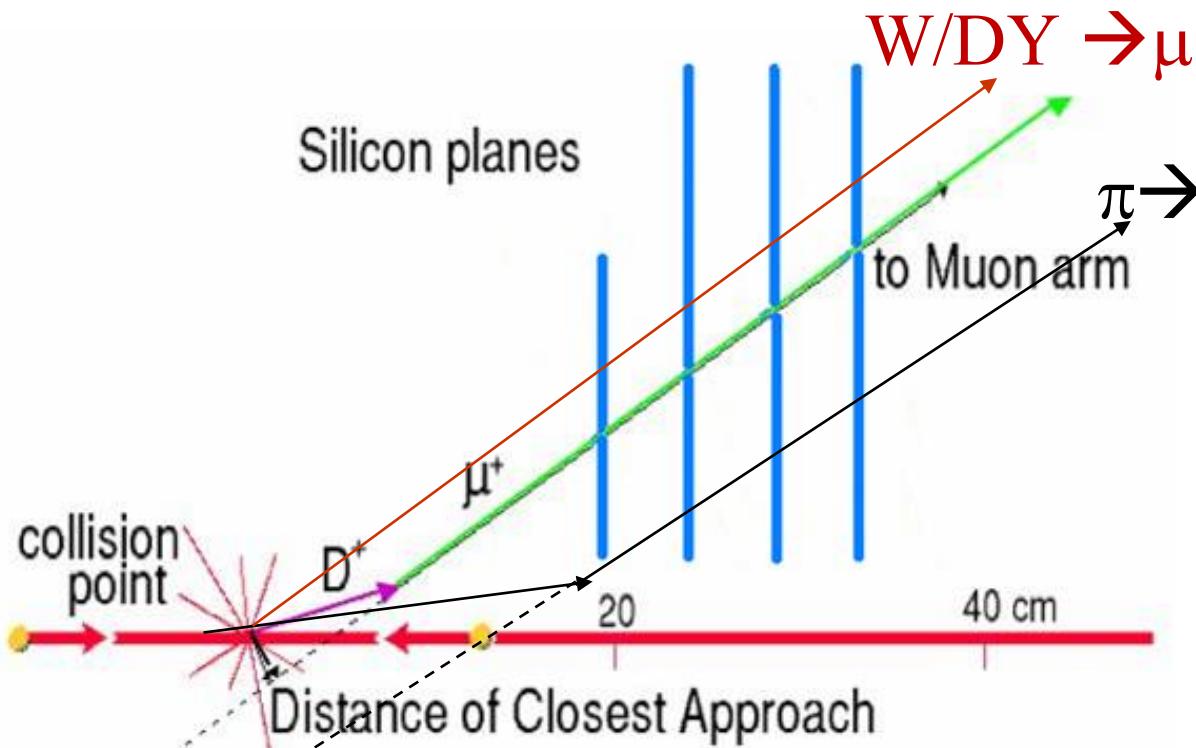
Heavy Flavor A_N VS x_F



FVTX installed in 2012

4 layers of FVTX end-caps cover $1.2 < |\eta| < 2.4$ with resolution $\sim 100\mu\text{m}$.

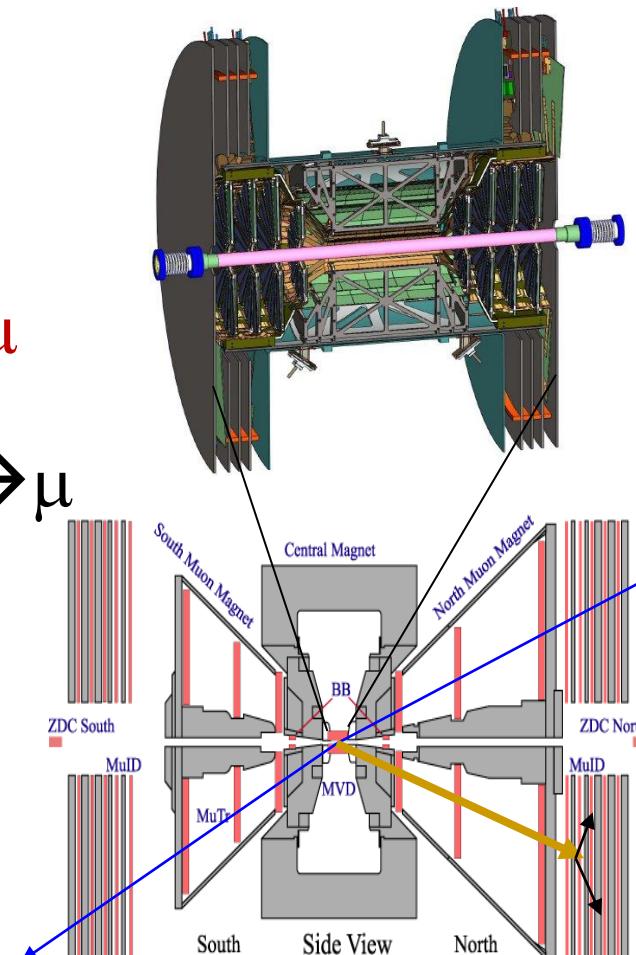
- ◆ Precise Charm/Beauty, W via single muon
- ◆ J/ ψ , Drell-Yan ... via dimuons



10/24/2014

INSTITUTE
STATE

Spin 2014



PHENIX

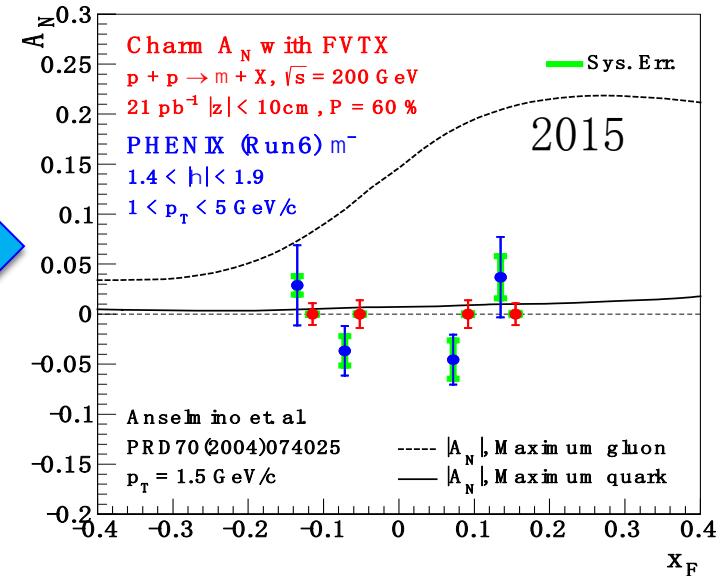
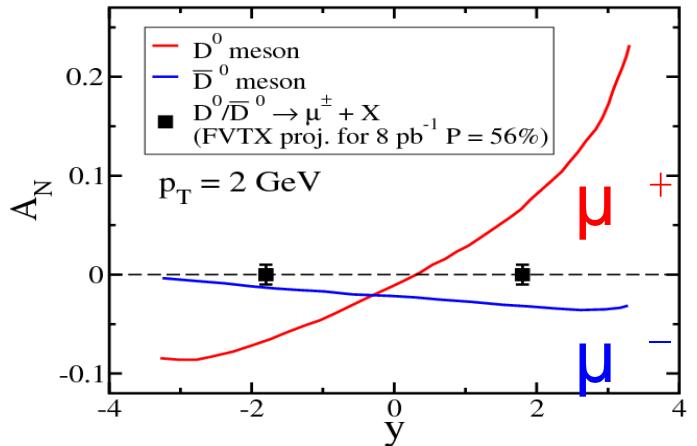
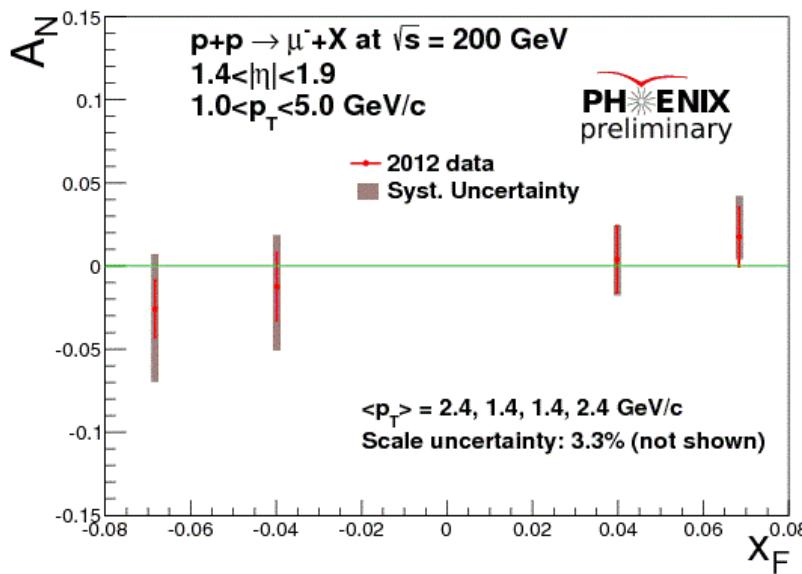
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Projected Open Charm A_N with FVTX

◆ Significant rejection of hadron background

◆ Challenging on D/B separation

◆ More transverse spin data expected from 2015



Summary & Outlook

- ◆ PHENIX measured the transverse single spin asymmetries consistent with zero in heavy flavor production at 200GeV in 2006, 2008 and 2012.
- ◆ The latest 2012 preliminary results bring down the statistical constraints on high transverse momentum bin from 20% to ~7%
- ◆ Forward silicon detector (FVTX) would play a significant role on S/B ratio improvement.
- ◆ Pursue the measurement in higher p_T bins ($>5\text{GeV}$) in 2015 run.

Back up

10/24/2014

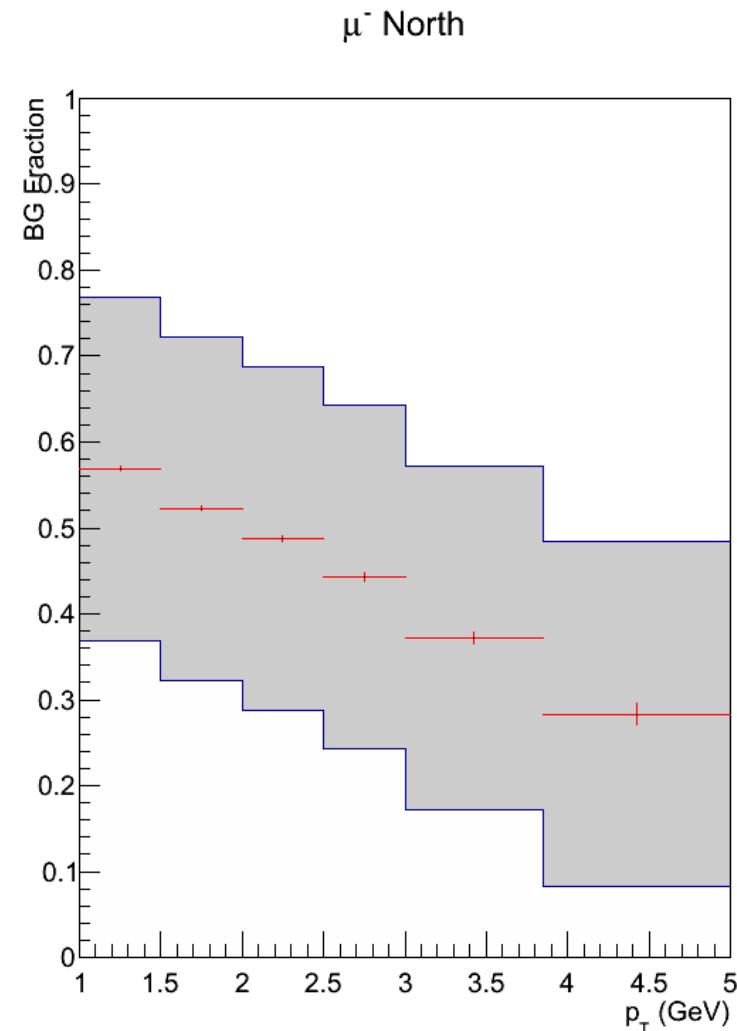
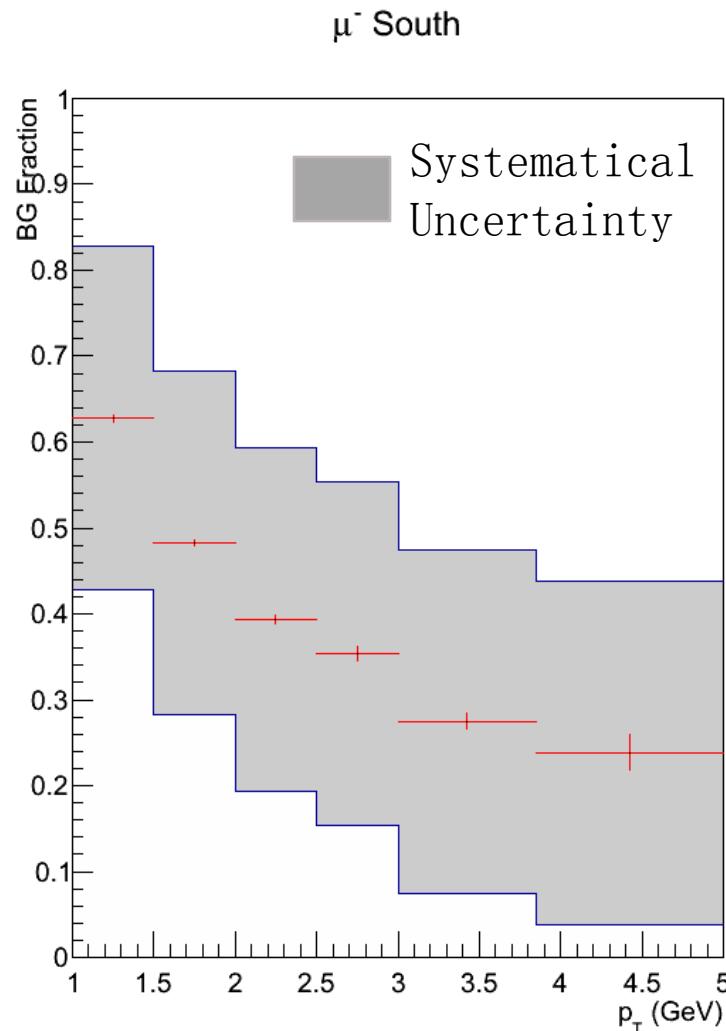


Spin 2014

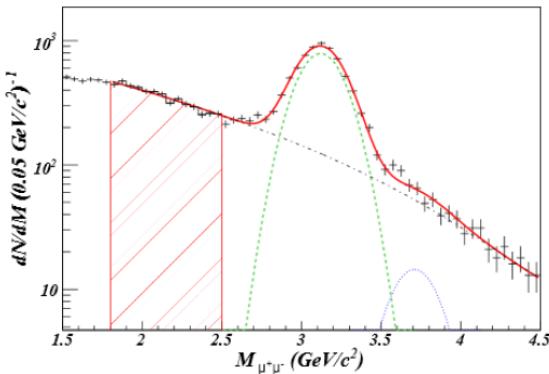


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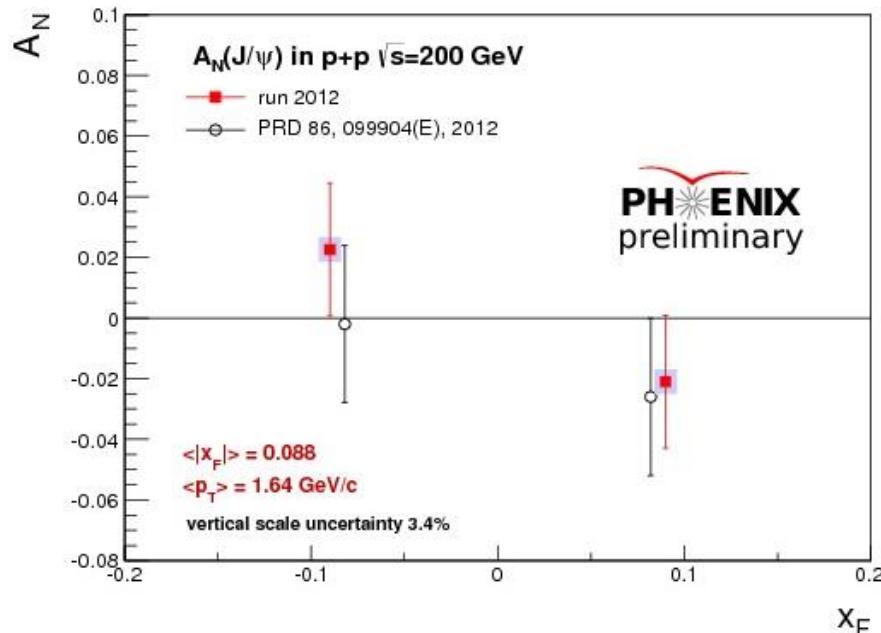
Background fraction



A_N of J/ψ



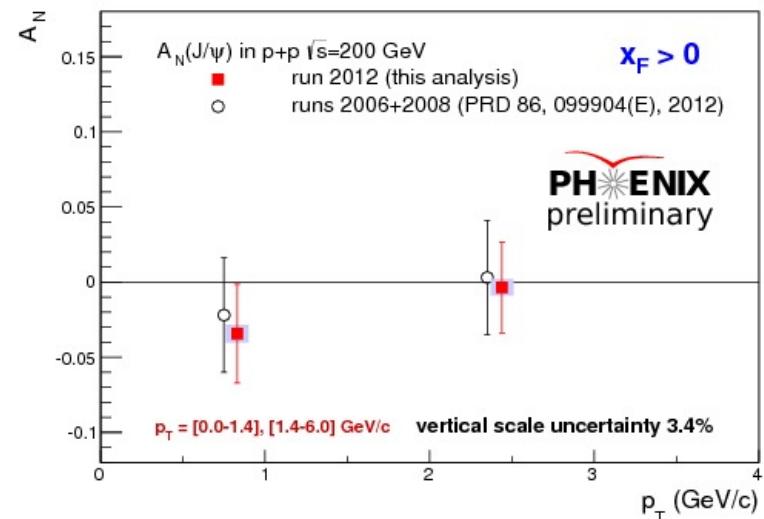
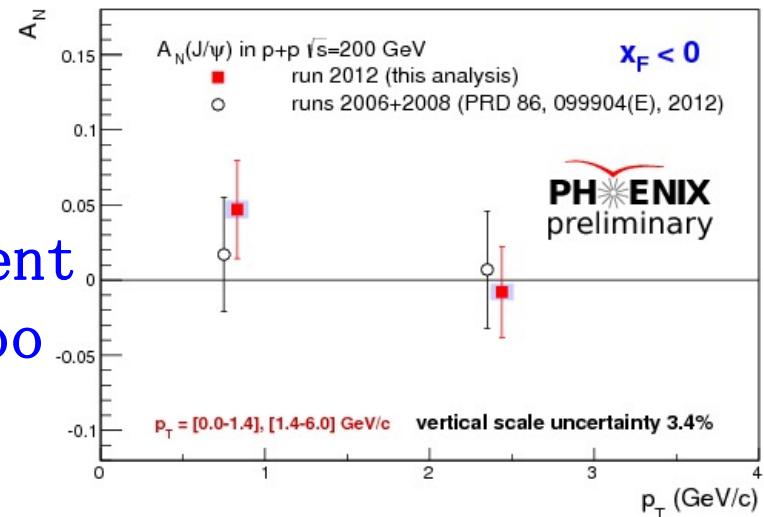
The results
are consistent
with zero too



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SPIN

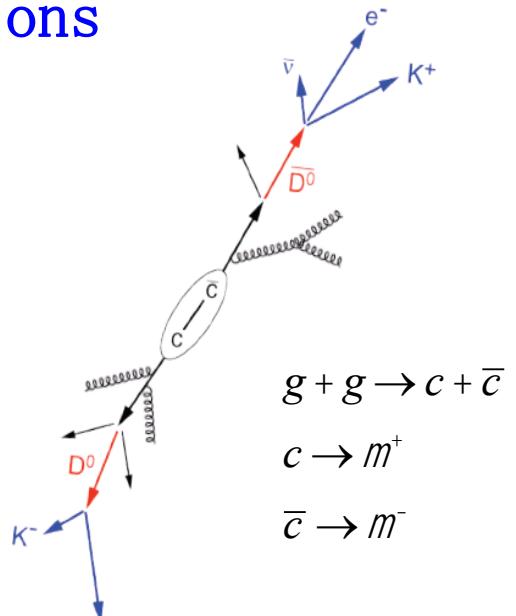


Heavy Quark TSSA at RHIC

Twist-3 tri-gluon correlation functions

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3 P_h} \simeq \frac{\alpha_s^2 M_N \pi}{S} \epsilon_{P_h p n S_\perp} \sum_{f=c\bar{c}} \int \frac{dx'}{x'} G(x') \int \frac{dz}{z^3} D_a(z) \int \frac{dx}{x} \delta(\tilde{s} + \tilde{t} + \tilde{u}) \frac{1}{\tilde{u}}$$

$$\times \left[\delta_f \left(\frac{d}{dx} O(x) - \frac{2O(x)}{x} \right) \hat{\sigma}^{O1} + \left(\frac{d}{dx} N(x) - \frac{2N(x)}{x} \right) \hat{\sigma}^{N1} \right].$$



where $O(x) \equiv O(x, x) + O(x, 0)$, $N(x) \equiv N(x, x) - N(x, 0)$.

$d_f = +1(c); -1(\bar{c})$

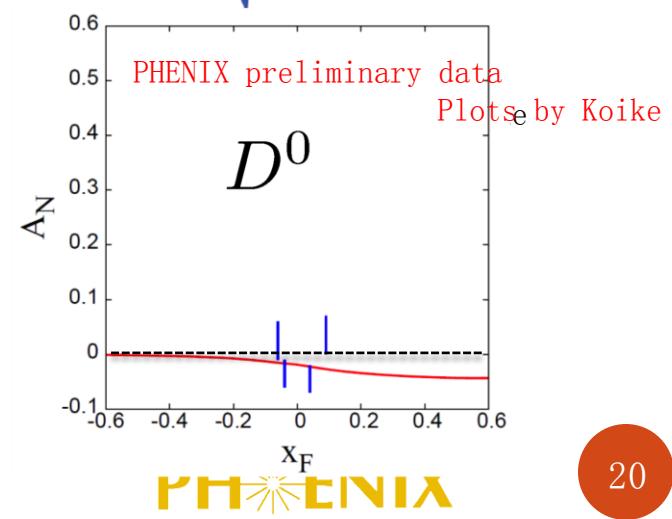
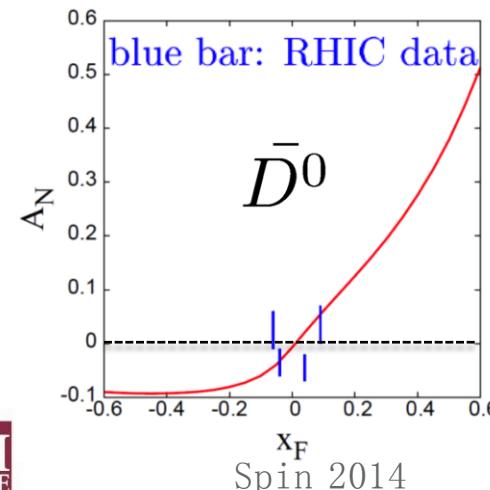
$$A_N(D) \stackrel{?}{=} A_N(\bar{D})$$

Model 1:

$$O(x) = 0.004xG(x)$$

Koike *et. al.* (2011)

Kang, Qiu, Vogelsang, Yuan (2008)



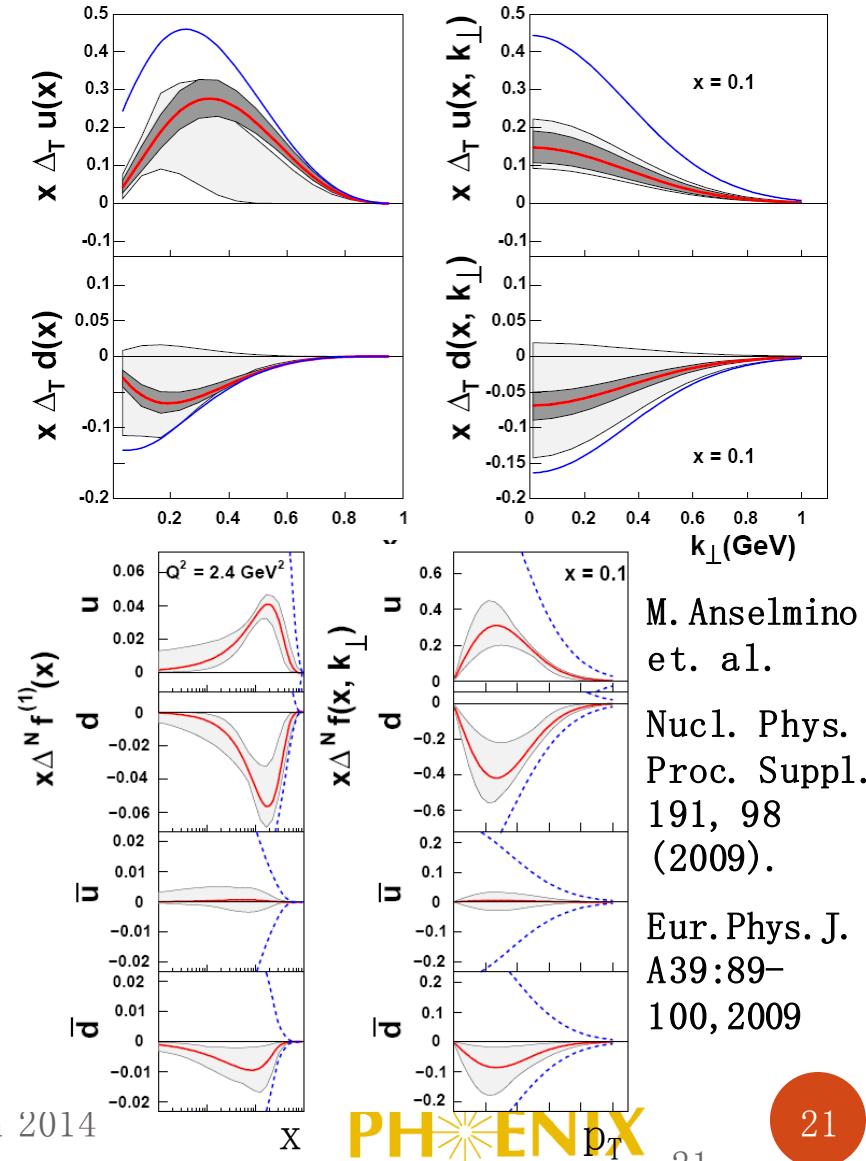
Spin in transversely polarized proton

- Quark transversity
 - Know much better about quark transversity than before.
- Gluon transversity
 - No transversely polarized gluon.
- Parton orbital angular momentum
 - The Sivers function could be related to orbital angular momentum.
 - **Quark Sivers function is constrained OK.**
 - **Gluon Sivers function is not well known.**

10/24/2014



Spin 2014



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Mechanisms in QCD

TMD mechanism – Explains SIDIS measurements very well

Possible Expansion:

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto f_{1T}^{\perp} \otimes D_1 + \delta q \otimes H_1^{\perp} + \dots$$

Sivers Function
(angular momentum)
↓
Sivers Effect

Transversity
(structure)

Collins Function
(Fragmentation)
↓
Collins Effect

Twist-3 mechanism – Explain RHIC measurements very well

At high transverse momenta : two twist-3 correlation functions

1. Quark-gluon correlation function $T_{q,f}$
2. Two independent trigluon correlation $T_G^{(f)}, T_G^{(d)}$ functions